

Autocorrelations of stellar light and mass in the low-redshift Universe

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ABSTRACT

The final data release of the Sloan Digital Sky Survey (SDSS) provides reliable photometry and spectroscopy for about half a million galaxies with median redshift 0.09. Here we use these data to estimate projected autocorrelation functions $w_p(r_p)$ for the light of galaxies in the five SDSS photometric bands. Comparison with the analogous stellar mass autocorrelation, estimated in a previous paper, shows that stellar luminosity is less strongly clustered than stellar mass in all bands and on all scales. Over the full nonlinear range $10h^{-1}\text{kpc} < r_p < 10h^{-1}\text{Mpc}$ our autocorrelation estimates are extremely well represented by power laws. The parameters of the corresponding spatial functions $\xi(r) = (r/r_0)^\gamma$ vary systematically from $r_0 = 4.5h^{-1}\text{Mpc}$ and $\gamma = -1.74$ for the bluest band (the u band) to $r_0 = 5.8h^{-1}\text{Mpc}$ and $\gamma = -1.83$ for the reddest one (the z band). These may be compared with $r_0 = 6.1h^{-1}\text{Mpc}$ and $\gamma = -1.84$ for the stellar mass. Ratios of $w_p(r_p)$ between two given wavebands are proportional to the mean colour of correlated stars at projected distance r_p from a randomly chosen star. The ratio of the stellar mass and luminosity autocorrelations measures an analogous mean stellar mass-to-light ratio (M_*/L). All colours get redder and all mass-to-light ratios get larger with decreasing r_p , with the amplitude of the effects decreasing strongly to redder passbands. Even for the u -band the effects are quite modest, with maximum shifts of about 0.1 in $u - g$ and about 25% in M_*/L_u . These trends provide a precise characterisation of the well-known dependence of stellar populations on environment.

Key words: galaxies: clusters: general – galaxies: distances and redshifts – cosmology: theory – dark matter – large-scale structure of Universe.

1 INTRODUCTION

Over the past three decades, redshift surveys of nearby galaxies have established that galaxies of different types are distributed in space in different ways (e.g. Davis & Geller 1976; Dressler 1980). Among the various galaxy properties that have been considered, colour is found to be among the most dependent on local environment density (Kauffmann et al. 2004; Blanton et al. 2005), with luminosity also a significantly environment-dependent property (Blanton et al. 2005). Two-point autocorrelation functions, the traditional quantitative characterisation of clustering, thus depend both on luminosity (Davis et al. 1988; Hamilton 1988; White et al. 1988; Boerner et al. 1989; Einasto 1991; Park et al. 1994; Loveday et al. 1995; Benoist et al. 1996; Guzzo et al. 1997; Norberg et al. 2001; Zehavi et al. 2002, 2005; Li et al. 2006; Wang et al. 2007; Swanson et al. 2008) and on colour (Willmer et al. 1998;

Brown et al. 2000; Zehavi et al. 2002, 2005; Li et al. 2006; Wang et al. 2007; Swanson et al. 2008). Measurements of correlation functions for different classes of galaxies provide powerful quantitative constraints on models of galaxy formation and evolution.

The Sloan Digital Sky Survey (SDSS; York et al. 2000) is the most ambitious optical imaging and spectroscopic survey to date. In Li & White (2009, hereafter Paper I) we studied the distribution of stellar mass in the local Universe using a complete and uniform sample of about half a million galaxies selected from the final data release (DR7; Abazajian et al. 2009) of the SDSS. This was quantified by two statistics: the abundance of galaxies as a function of stellar mass $\Phi(M_*)$, which we estimated over the stellar mass range $10^8 < M_* < 10^{12}h^{-2}\text{M}_\odot$, and the projected stellar mass autocorrelation function $w_p^*(r_p)$, which we estimated over the projected separation range $10h^{-1}\text{kpc} < r_p < 30h^{-1}\text{Mpc}$. Both statistics were robustly and precisely determined for the masses and scales probed. We found $w_p^*(r_p)$ to be remarkably well described by a power law, a behaviour

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which is approximately, but not perfectly reproduced by existing galaxy formation models. These measurements have been used in Guo et al. (2009) to link the stellar masses of galaxies to the dark matter masses of their haloes.

In this short paper we extend the work of Paper I by estimating projected *luminosity* autocorrelation functions. We use exactly the same methodology and the same galaxy sample as in Paper I. We compute luminosity autocorrelation functions for the five passbands of SDSS, and compare these with the stellar mass autocorrelation function obtained in Paper I. For each case we provide the parameters of the best-fitting power-law. By taking ratios of these autocorrelations we investigate the scale-dependence of the mean colours and mean mass-to-light ratios of clustered stellar populations. Finally, we discuss briefly how our results relate to other measures of the distribution of stellar light and mass in the low-redshift Universe.

2 STELLAR LUMINOSITY AUTOCORRELATION FUNCTIONS

We use the same galaxy sample as in Paper I except that we have dropped those galaxies with r -band absolute magnitude $M_{0.1,r} < -24$ or $M_{0.1,r} > -16$. This reduces the sample by less than 1% so that it now consists of 482 755 galaxies. We use SDSS Petrosian magnitudes so that for each galaxy the luminosities, colours and stellar mass are all measured within a single well-defined aperture (defined to be twice the r -band Petrosian radius). Our methodology for estimating projected autocorrelation functions and for constructing the random sample necessary for such estimates is also identical to that in Paper I: the stellar masses of the pair members, $M_{*,i}$ and $M_{*,j}$ in Eqs. 3-5 of Paper I, are simply replaced by the corresponding luminosities, $L_{\alpha,i}$ and $L_{\alpha,j}$. Here α denotes the passband being considered which is one of the five bands of SDSS: u , g , r , i , or z . The luminosities are K -corrected to their values at $z = 0.1$ (see Blanton et al. 2003b; Blanton & Roweis 2007), and are corrected for evolution following Blanton et al. (2003a).

Our estimates of the projected luminosity autocorrelation functions, $w_p^L(r_p)$, are plotted in Fig. 1 for the five SDSS bands and are compared with the projected stellar mass function, $w_p^*(r_p)$. Error bars on $w_p^*(r_p)$ are estimated from the scatter between the results found when exactly the same methodology is applied to our 20 mock SDSS samples (see Paper I for details). We do not attempt to put independent error bars on the projected luminosity autocorrelations because with our technique the set of galaxy pairs used to estimate each of these functions is *exactly* the same, both in the real data and in the mock catalogues. As a result, the realisations of sampling noise, large-scale structure noise (“cosmic variance”) and background subtraction noise are identical in all our autocorrelation estimates. Only the colour and stellar mass-to-light ratio distributions of individual pair members are differently sampled for the different functions. Since very large numbers of galaxies contribute to each autocorrelation estimate and these distributions are narrow, they do not contribute significantly to the error budget.

Fig. 1 shows that luminosity clusters less strongly than stellar mass on all scales, regardless of which waveband we consider. Furthermore, the amplitude of clustering increases

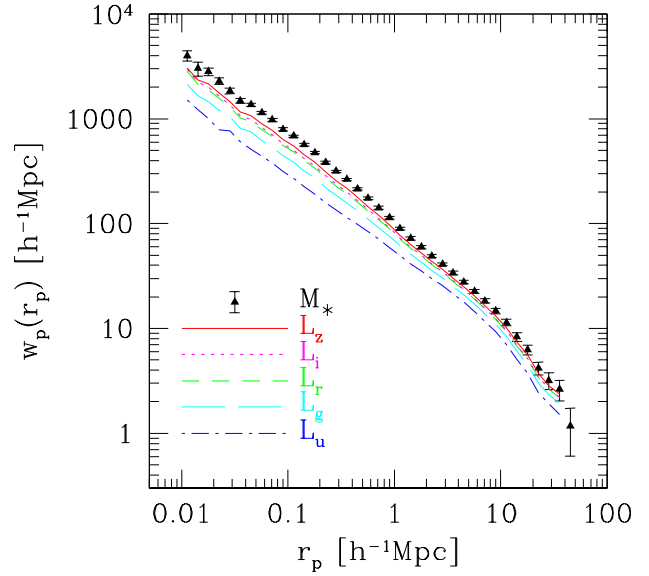


Figure 1. The projected stellar mass autocorrelation function in the SDSS is plotted as triangles with error bars and is compared to the projected luminosity autocorrelation functions measured for the five passbands of SDSS (the lines). Errors on the stellar mass autocorrelation function are estimated from the scatter among the measurements from 20 mock galaxy catalogues constructed from the Millennium Simulation (Springel et al. 2005) using the same selection criteria as the real sample.

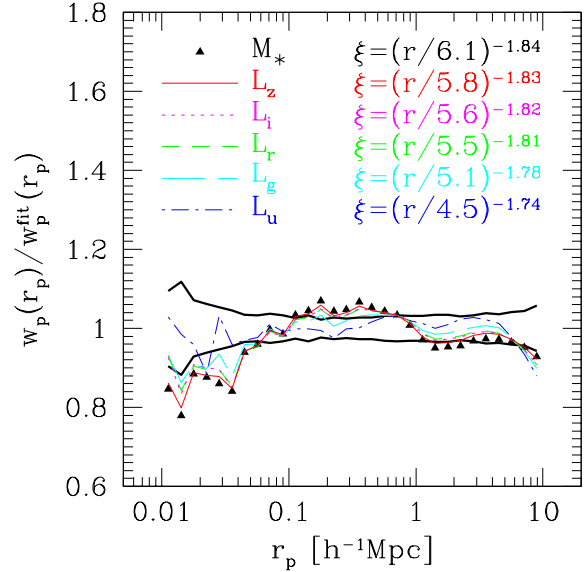


Figure 2. Ratio of the projected stellar mass (triangles) or luminosity (thin lines) autocorrelation functions in the SDSS to the individual best fit power-laws over the range $10 h^{-1} \text{kpc} < r_p < 10 h^{-1} \text{Mpc}$. The correlation length r_0 and the power-law slope γ of the corresponding three-dimensional autocorrelation function $\xi(r) = (r/r_0)^\gamma$ are indicated. The thick lines above and below unity indicate the $1-\sigma$ scatter of the stellar mass autocorrelation functions estimated from 20 mock galaxy catalogues constructed from the Millennium Simulation (Springel et al. 2005) to have the same selection effects as the real sample.

systematically with increasing wavelength on all scales. Beyond about $2h^{-1}\text{Mpc}$ the autocorrelation functions are all parallel to each other. This is easily understood within the Halo Occupation Distribution (HOD) formalism as a consequence of the fact that pairs at these separations almost all consist of galaxies which are members of two different halos (e.g. Cooray & Sheth 2002). On smaller scales the autocorrelation functions become steeper with increasing wavelength. This is the regime where there is a substantial contribution from pairs which are members of the same halo and the change in shape may reflect a colour-dependence of the weights given to halos of different mass, a colour-dependence of the distribution of galaxies within a given halo, or (more likely) both.

Between $10h^{-1}\text{kpc}$ and $10h^{-1}\text{Mpc}$ the autocorrelation functions are all well described by power laws. This is shown more clearly in Fig. 2 where we plot the ratio of each to the power law that best fits it over this r_p range. Values of r_0 and γ for the corresponding three-dimensional autocorrelation functions $\xi(r) = (r/r_0)^\gamma$ are indicated in the figure. The result for the stellar mass correlation function is plotted as triangles for comparison. The two thick lines indicate the $1 - \sigma$ scatter about the mean for stellar mass correlation functions estimated from 20 mock SDSS samples constructed from the Millennium Simulation (Springel et al. 2005; Croton et al. 2006). The *rms* deviations from a power law are 4, 5, 6, 6, 7 and 7 percent for the u , g , r , i and z band autocorrelations and for the stellar mass autocorrelation, respectively. These are quite comparable to the *rms* uncertainty of 5 percent which we estimate for all these autocorrelations from our 20 mock catalogues over the same r_p range.

3 COLOUR AND STELLAR MASS-TO-LIGHT RATIO DISTRIBUTIONS

If we take the ratio of our projected luminosity autocorrelation functions in two bands, for example u and g , we can write

$$\begin{aligned} w_p^{Lu}(r_p)/w_p^{Lg}(r_p) &= \frac{\langle L_{u,1}L_{u,2} \rangle_{r_p} / \langle L_u \rangle^2}{\langle L_{g,1}L_{g,2} \rangle_{r_p} / \langle L_g \rangle^2} \\ &= \frac{\langle (L_{u,1}/L_{g,1})(L_{u,2}/L_{g,2})L_{g,1}L_{g,2} \rangle_{r_p}}{\langle L_{g,1}L_{g,2} \rangle_{r_p}} \\ &\quad \div \frac{\langle (L_u/L_g)L_g \rangle^2}{\langle L_g \rangle^2}, \end{aligned}$$

where $\langle \dots \rangle_{r_p}$ denotes an average over all *correlated* pairs of galaxies with projected separation r_p , and $\langle \dots \rangle$ denotes an average over all individual galaxies. The second equality here shows that this autocorrelation ratio can be thought of as the luminosity-weighted (hence, approximately, per star weighted) average of the product of the luminosity ratios L_u/L_g of the pair members, relative to the square of the luminosity-weighted average of the same ratio for individual galaxies. Hence we can define a characteristic host galaxy colour for pairs of stars separated by r_p through, for example,

$$(u - g) - \langle u - g \rangle = -1.25 \log_{10}(w_p^{Lu}(r_p)/w_p^{Lg}(r_p)). \quad (1)$$

This quantity is shown in Fig. 3 as a function of r_p for the four colour indices defined by neighboring pairs of SDSS

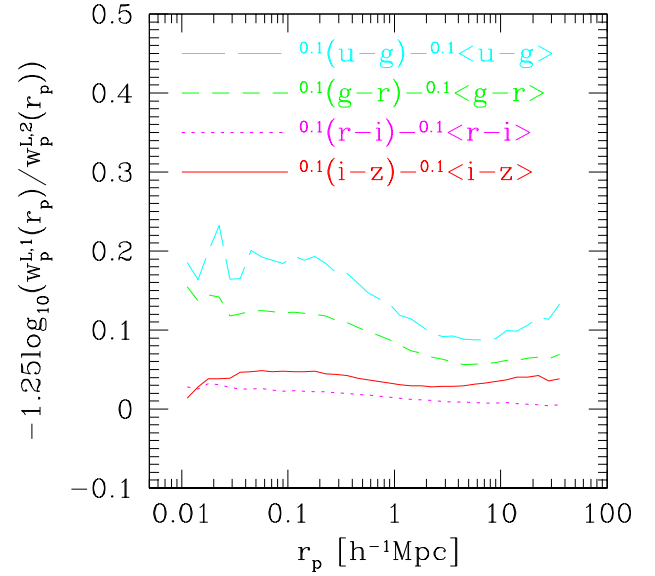


Figure 3. Mean colours of all correlated stars at projected distance r_p from a randomly chosen star relative to the luminosity-weighted average values of individual galaxies. These can be estimated directly from ratios of the projected autocorrelation functions in Fig. 1.

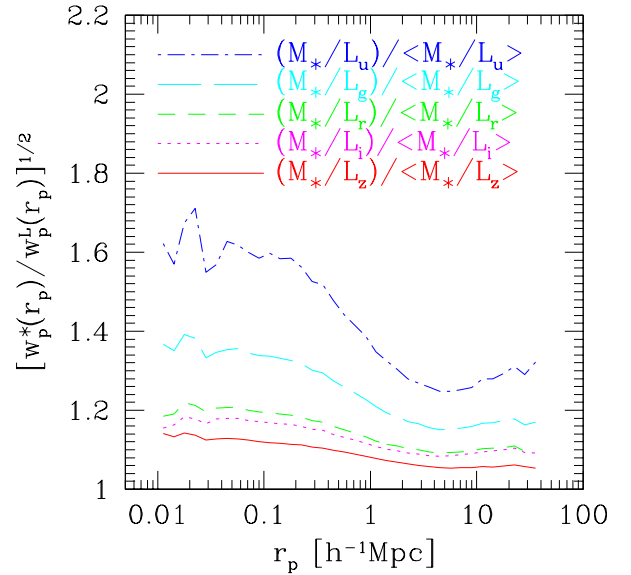


Figure 4. Mean mass-to-light ratios for all correlated stars at distance r_p from a randomly chosen star relative to the luminosity-weighted average values for individual galaxies. These can be estimated directly from ratios of the stellar mass and light autocorrelations in Fig. 1.

filters. The results are consistent with host galaxy colour being independent of scale both at large ($r_p > \text{a few Mpc}$) and at small ($r_p < \text{a few 100 kpc}$) separations. The scale-dependence at intermediate separations is strongest for $^{0.1}(u-g)$ although even here it amounts to a total variation of less than 0.1 magnitudes. The variation in colour is weaker

for redder colours and is essentially absent for the reddest bands.

Replacing the luminosity autocorrelation function in the numerator of Eq. 1 by the projected stellar mass autocorrelation function produces an estimate of (the square of) the typical mass-to-light ratio of the host galaxies of (correlated) star pairs separated by r_p , relative to the luminosity-weighted average value for individual galaxies. We plot this quantity for the five SDSS photometric bands in Fig. 4. The scale-dependence of M_*/L is similar to that of the colours: a transition to lower values occurs between a few 100 kpc and a few Mpc, but M_*/L is independent of scale on both smaller and larger scales. Again effects are strongest in u and get weaker with increasing wavelength, but in this case a small but significant trend is seen even in the z -band. M_*/L_u increases by about 25% from large to small scales.

The trends shown in this section are all easily understood as reflecting the fact that pairs of small separation are typically members of the same halo, whereas pairs at large separation must belong to different halos. This results in a different weighting with halo mass in the two regimes. In particular, close (‘one halo’) pairs are more strongly weighted towards massive halos than are distant (‘two halo’) pairs. In the former case at least one of the two galaxies must be a satellite object, whereas in the latter case both galaxies are often the central galaxy of their own halo. These trends result in a greater contribution from early-type “red-and-dead” galaxies to the small-scale correlations.

4 DISCUSSION

Just as was the case for the projected stellar mass autocorrelation function presented in Paper I, projected autocorrelation functions of luminosity in each of the five SDSS bands are robustly and precisely determined by our methods for $r_p < 30h^{-1}\text{Mpc}$. Over the full nonlinear range $10h^{-1}\text{kpc} < r_p < 10h^{-1}\text{Mpc}$, they are all extremely well represented by power laws with corresponding three-dimensional correlation lengths r_0 and power-law indices γ which vary slightly but systematically from band to band. As pointed out in Paper I, this power-law behaviour must be seen as a coincidence in our standard structure formation model, and different processes are required to cause convergence to the observed power law on different scales and in different bands. If the “one-galaxy” term in the mass and luminosity autocorrelations is included there is a strong upward break at the scale of individual galaxies.

Our measured luminosity autocorrelations quantify the extent to which the spatial distribution of optical light in the local Universe depends on scale and wavelength. The relative bias between the longest and shortest wavebands varies from a factor of 1.5 on small scales ($< 100\text{kpc}$) to a factor of 1.2 on large scales ($> \text{a few Mpc}$). Luminosity in all bands and on all scales clusters less strongly than stellar mass, although for z -band luminosity the difference is small. This is consistent with previous studies which have found z -band light to be a good tracer of stellar mass (e.g. Kauffmann et al. 2003).

All the autocorrelation functions considered in this paper have very similar shape on large scales ($> 5\text{Mpc}$). This is expected in models where the properties of galaxies de-

pend on the detailed formation history within their own dark matter halos, but are independent of the formation histories of distant halos. On smaller scales the shape of the various autocorrelation functions differ, reflecting differences in the relative strength of the one-halo and two-halo contributions which arise from a combination of effects. One-halo correlations are more heavily weighted towards massive halos than are two-halo correlations, and red and high M_*/L galaxies are typically found in more massive halos than blue galaxies of similar mass. Small-scale correlations are also sensitive to how satellite galaxies are distributed with radius within their dark halos (see Weinmann et al. 2006 and von der Linden et al. 2009 for recent observational studies demonstrating that these radial distributions do indeed depend on galaxy colour and M_*/L). The precise quantitative results we obtain in this paper, when combined with accurate luminosity and stellar mass functions, provide a compact way to constrain Halo Occupation Distribution models which try to represent all these relations in detail (e.g. Watson et al. 2009).

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